

Demonstration of SiC Pressure Sensors at 750 °C

Robert S. Okojie¹, Dorothy Lukco², Vu Nguyen³, and Ender Savrun³

¹NASA Glenn Research Center, M/S 77-1, 21000 Brookpark Road, Cleveland, OH 44135

²Vantage Partners, LLC, NASA Glenn Research Center, Cleveland, OH 44135

³Sienna Technologies, Inc, 19501 144th Ave NE # F500, Woodinville, WA 98072

ABSTRACT

We report the first demonstration of MEMS-based 4H-SiC piezoresistive pressure sensors tested at 750 °C and in the process confirmed the existence of strain sensitivity recovery with increasing temperature above 400 °C, eventually achieving near or up to 100 % of the room temperature values at 750 °C. This strain sensitivity recovery phenomenon in 4H-SiC is uncharacteristic of the well-known monotonic decrease in strain sensitivity with increasing temperature in silicon piezoresistors. For the three sensors tested, the room temperature full-scale output (FSO) at 200 psig ranged between 29 and 36 mV. Although the FSO at 400 °C dropped by about 60 %, full recovery was achieved at 750 °C. This result will allow the operation of SiC pressure sensors at higher temperatures, thereby permitting deeper insertion into the engine combustion chamber to improve the accurate quantification of combustor dynamics.

Key words: Silicon carbide, high temperature, pressure sensor, sensitivity recovery.

Introduction

There is ongoing effort to lower greenhouse gas emissions from air vehicles by 50 % by 2050, relative to 2005 numbers, and improve fuel combustion efficiency by 2 %/year to 2020 as part of the ICAO (International Civil Aviation Organization) goals [1]. Lean burning (LB) (i.e., lower fuel/air ratio), has been demonstrated to further reduce undesirable emissions and increase combustion efficiency. However, LB increases the potential for thermoacoustic instability, which is the precursor to flame-out or possible engine damage [2]. This instability must be detected early, preferably at the start of nucleation, and controlled. In addition to the above application, future engine design and production will be driven more by computers. Input to such design and production processes would be largely sourced from computational fluid dynamics (CFD) codes that must be validated to accurately predict the optimal engine performance across the operating conditions. However, the high uncertainty errors that exist in these CFD codes, specifically in the high temperature regime, require that these codes be experimentally validated with sensors that are reliable and robust at high temperature.

Pressure sensors are used to measure both static and dynamic pressures during engine tests. The state-of-the-art silicon-based pressure sensors can operate reliably up to about 350 °C, albeit with water cooling jackets in order to avoid degradation and to maintain measurement integrity. Commercially available pressure sensors that utilize quartz crystals are specified to operate up to 400 °C without water cooling [3], and the only known commercially available dynamics-only pressure sensors uses GaPO₄ piezoelectric crystals that are reported to operate between 400 and 780 °C [4, 5]. This material must be synthesized since it does not exist in nature, and there is only one known global manufacturer. Currently, there is no commercially available static micro pressure sensor that can operate at temperatures higher than 350 °C without cooling. In order to ensure measurement integrity during use in combustor condition diagnostics, these pressure sensors are placed several inches away from the hot sections through an infinite loop tube. Such measurement strategy causes the attenuation of key frequency components and delay in pressure propagation, thus affecting signal fidelity. It also diminishes the opportunity to be applied for real time active control of combustion instabilities.

Silicon carbide (SiC) piezoresistive pressure sensors have been demonstrated to operate at 600 °C. As in silicon, the sensitivity to pressure of SiC piezoresistors monotonically decrease with increasing temperature, as evidenced by the decreasing full-scale output (FSO) tending to level off to about 40 % of the room temperature value at approximately 400 °C. However, we have been observing an interesting phenomenon in which the SiC sensor FSO begins an upward swing as the temperature exceeds 400 °C. At 600 °C the piezoresistance has increased to about 65 % of its room temperature from 40 % at 400 °C [6]. Until now, it was not possible to reliably test the SiC pressure sensors beyond 600 °C due to the limit imposed by the contact metallization. However, recent advancement in contact metallization technology has enabled the extension of the SiC pressure sensor operation to 750 °C, thereby making it possible to observe the full extent of the FSO recovery.

Sensor Fabrication

The complete description of the preparation of the sensors can be found in [7]. Briefly, piezoresistive pressure sensors were fabricated in an n-type 4H-SiC epitaxial layer that was homoepitaxially grown on a semi-insulating 4H-SiC wafer. Such configuration ensures very minimal junction thermal leakage current between the n-type layer and the semi-insulating wafer. For the contact metallization, the piezoresistors were initially metallized with a stack of Ti (100 nm)/TaSi₂ (400 nm)/Pt (300 nm). After photolithographic pattern definition the Pt layer was etched in 10:9:1 mixture of H₂O:HCl:HNO₃ (*aqua regia*) at 70 °C for 8 minutes to create a circular contact pad on the piezoresistors. Another layer of TaSi₂ (400 nm) was deposited, at

which point the underlying TaSi₂ and the top TaSi₂ encased the circular Pt layer. Another contact pattern was defined on the top TaSi₂ to align with the Pt circular pad. Etching of the now 800 nm TaSi₂ and 150 nm Ti on the field was performed with buffered oxide etch, followed by furnace anneal at 650 °C for 30 minutes in 5 slpm Ar ambient. This anneal process establishes the Ti ohmic contact to SiC and promotes zone reactions to form a diffusion barrier layer of platinum silicide against Au diffusion. Another deposition of TaSi₂ (100 nm)/Pt (200 nm)/TaSi₂ (400 nm)/Pt (300 nm) was performed, which was followed by a 2 µm aluminum (Al) deposition. Contact pad pattern was defined in Al and etched in H₃PO₄ at 50 °C. Using the Al as an etch mask, the layers were etched by reactive ion etching using the following set of conditions: Ar=140 sccm, SF₆=5 sccm, Pressure=25 mT, and Power=300 W (RF). After etching, the residual Al etch mask was stripped and the wafer was furnace annealed under conditions described above. Finally, W (200 nm)/Au (1000 nm) bond pad deposition was performed to cap the contacts. The tungsten layer acts as another diffusion barrier layer against Au. The Au layer facilitates excellent wettability to the Au die-attach paste that was used as the metallurgical joint between the Au bond pads and the connecting external Au wires during packaging. The wafer was diced into chips and individually packaged.

Sensor Testing and Results

Three 4H-SiC pressure sensors were tested at various pressures and temperatures up to 750 °C. The results are shown in Figs. 1 (a-c). In the three figures, the net output voltage as function of pressure at different temperatures shows a consistent drop in output with increasing temperature up to about 400 °C, beyond which a gradual increase is observed. At 750 °C, the net output voltage has practically recovered to or near the respective room

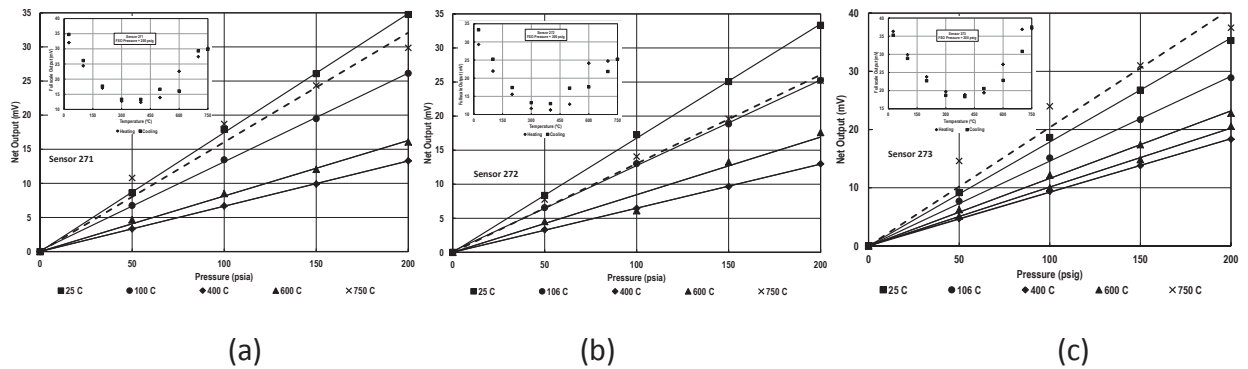


Fig. 1 a-c: Net output voltage of 4H-SiC pressure sensors as function of pressure and at different temperatures up to 750 °C. The inset graphs are the respective FSO as function of temperature.

temperature values. This response of the net output (as shown in inset) suggests that the piezoresistance of the SiC semiconductor has parabolic characteristics. To the best of our knowledge, this is the first reported case of a semiconductor piezoresistive sensor operation at 750 °C, and also the first reported case of bipolar piezoresistance in SiC semiconductor. While further study is underway to understand the basis of this parabolic behavior, one speculation is that based on the multi-valley energy level interactions within the SiC, the piezoresistance in the relatively lower bandgap (1.12 eV) silicon site is more dominant from lower temperatures to 400 °C. Above 400 °C, however, the piezoresistance of the wider bandgap (5.48 eV) of the carbon site is more dominant. The piezoresistance of silicon as function of temperature is well known to decrease monotonically with increasing temperature. In contrast, carbon piezoresistors grown by chemical vapor deposition have been reported to exhibit increasing gauge factor (piezoresistance) with increase in temperature [8, 9]. A more comprehensive investigation of this phenomenon based on multi-valley charge transport and piezoresistance at extended temperatures will be required in order to fully understand the prevailing mechanisms.

Conclusion

The operation of 4H-SiC pressure sensors at 750 °C were demonstrated for the first time. The resulting parabolic response of the FSO as function of temperature, in which the net output at 750 °C reaches the room temperature values, reveal the existence of parabolic piezoresistivity behavior in SiC semiconductor. This result opens opportunity to further extend SiC pressure sensor operation to higher temperatures.

Acknowledgement

The funding for this work was provided by the NASA Aeronautical Sciences Project under the Fundamental Aeronautics Programs. The authors thank the technical staff of the NASA Glenn Research Center SiC microfabrication laboratory for the successful fabrication of the sensors.

References

1. <http://www.icao.int/environmental>.
2. AH. Lefebvre, "Gas Turbine Combustion", 2nd edition, Taylor & Francis, 1999.
3. http://www.pcb.com/TestMeasurement/Pressure/Extreme_Environ.aspx.
4. https://www.avl.com/c/document_library.
5. <http://www.vibro-meter.com/pdf/Cp215e.pdf>.

6. R.S. Okojie, V. Nguyen, E. Savrun, and D. Lukco, "Improved reliability of SiC pressure sensors for long term high temperature applications," 16th International Conference on Solid-State Sensors, Actuators and Microsystems (Transducer 2011), p. 2875 – 2878. 2011
7. R.S. Okojie, D. Lukco, C. Blaha, V. Nguyen, and E. Savrun, "Zero offset drift suppression in SiC pressure sensors at 600 °C," IEEE Sensors, p. 2269-2274. 2010.
8. M. Aslam, I. Taher, A. Masood, M. A. Tamor, and T. J. Potter, "Piezoresistivity in vapor deposited diamond films," Applied Physics Letters, 60, p. 2923. 1992.
9. W.L. Wang, X. Jiang, K. Taube, and C.-P. Klages, "Piezoresistivity of polycrystalline p -type diamond films of various doping levels at different temperatures," Journal of Applied Physics, 82, p. 729. 1997.